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SURVEY OF TECHNOLOGY ON COMMUNICATION THROUGH THE PLASMA SHEATH

(2438-6)

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The Ohio State University

ElectroScience Laboratory

Department of Electrical Engineering
Columbus, Ohio 43212

TECHNICAL REPORT AFAL-TR-70-123

July 1970

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Air Force Avionics Laboratory
Air Force Systems Command
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NOTICE

SURVEY OF TECHNOLOGY ON COMMUNICATION THROUGH THE PLASMA SHEATH

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FOREWORD

This report, OSURF Report Number 2438-6, was prepared by The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering at Columbus, Ohio. Research was conducted under Project 4062 of the Air Force Avionics Laboratory at Wright Patterson Air Force Base, Ohio. Mr. Robert Rawhouser, AVWE, of the Air Force Avionics Laboratory at Wright-Patterson Air Force Base, Ohio was the AFAL Program Monitor for this research under Contract Number F33615-67-C-1643.

This report was submitted by the author 24 April 1970.

This technical report has been reviewed and is approved for publication.

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for RONALD G. STIMMEL
Acting Chief
Electronic Warfare Division

ABSTRACT

A review of the state of the art in techniques for alleviating radio blackout during atmospheric reentry is presented. The various techniques currently being studied by those organizations interested in this problem include: injection of coolants and electrophilics, magnetic windows, electron beam devices, vehicle shaping, electrostatic charge collection and the use of high and low frequencies. The relative advantages and disadvantages of these methods are discussed. With the exception of simple, pointed, ballistic vehicles, the only flight experiments to date concerned specifically with alleviation have been on injection devices. The report concludes that these devices have many limitations and that the time has come to flight test other types of systems; the magnetic window is the most promising in the light of recent developments in superconducting technology.

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2438-1 "Trip Report Minutes on the Discussion of Communication Through the Reentry Plasma Sheath, Part I,"(U) 1 June 1967, (Report Secret)

2438-2 "Trip Report Minutes on Discussion of Communication Through the Reentry Plasma Sheath, Part II," 1 October 1967. (AD 821 931)

2438-3 "Reentry Communications: A Review of Fluid Mechanic and Electromagnetic Problems and Progress," 31 July 1968.

2438-4 "Payload Description Document, Trailblazer II DA-1619," 24 July 1968

2438-5 "VHF Reentry Communications; Flight Test Measurements Using a Trailblazer II Vehicle and Including a Test of the Aerodynamic Gas Spike," (Report in preparation).

2438-6 Final Report, 1 May 1967 to 28 February 1970, April 1970

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"Radiation by a VHF Dipole-Type Antenna Imbedded in its Plasma Sheath," R.V. DeVore and R. Caldecott. Presented at Conference on Environmental Effects on Antenna Performance, Boulder, Colorado, (1969).

"Antenna Noise Level and Impedance in a Reentry Environment, (Flight Test Results Using a Trailblazer Vehicle and Some Related Laboratory Studies)," Ross Caldecott, John Mayhan and Peter Bohley. Presented at The Conference on the Applications of Plasma Studies to Reentry Vehicle Communications, Wright-Patterson Air Force Base, Ohio, (October 1967).

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SURVEY OF TECHNOLOGY ON COMMUNICATION THROUGH THE PLASMA SHEATH

I. INTRODUCTION

Considerable effort has been concentrated on the reentry communications blackout problem for more than a decade. Three plasma sheath symposia[1, 2, 3] and one conference on applications of plasma studies to reentry problems[4] have been held. Most of the papers presented at these meetings are not addressed to the problem solution, but to discussion of the problem, measurements, etc. The first critical review and assessment of the problem was performed by the Plasma Research Laboratory of Aerospace Corporation[5]. It is the purpose of this report to update the Aerospace review by presenting an engineering assessment of any new methods suggested since the original review and indicating any significant trends in approach. This critique of course is not exhaustive - only the methods or techniques that have received considerable attention and/or indicate some further promise will be discussed.

In 1966[5] the prominent methods of alleviating the deleterious effects in communication through the sheath were: 1) aerodynamic shaping of the reentry vehicle, 2) magnetic window, 3) coolant injection, 4) injection of electron attaching gases etc., 5) utilization of expanding flows, and 6) frequencies above plasma resonance, including optical. These categories are rather all encompassing and almost any alleviation scheme would fall within one or more of them. In the course of the survey of current research on reentry problems, most of the major laboratories and research facilities concerned were visited. Their work was compiled and reported[6]. In early 1966 Aerospace considered in the order listed the most promising schemes to be:

1. Local aerodynamic shaping
2. Coolant injection into a non-expanding flow
3. Electrophilic injection into an expanding flow
4. Magnetic window using a conventional magnet. Use of a superconducting magnet was considered to be of limited utility.
5. High frequency antennas to include millimeter waves and lasers. These required a state of the art advance.

Each of these methods with the possible exception of high frequencies is still the subject of active research as a potential alleviation technique. High frequencies have not proved to be the success that was first hoped

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for because, while they may solve the reentry blackout problem, they introduce a host of new problems related to transmission through the atmosphere. Millimeter wave transmission at wavelengths less than 8 mm is limited to a few narrow windows in the oxygen and water vapor absorption spectra. Lasers present many problems of beam pointing and are also subject to the effects of thermal gradients and atmospheric turbulence. While the outlook for the use of high frequencies appears to have deteriorated, that for a magnetic window has improved considerably in the past four years. This is due to the considerable advances that have been made in cryogenics and superconducting magnet technology during this period.

The prime purpose of this program has been to survey the current state of the art in plasma blackout alleviation. The results of this survey have already been reported in References 4 and 6. To review the review would be superfluous in this final report and no attempt will be made so to do. Instead a very brief discussion of those topics which are presently the subject of active research or which are new to the blackout alleviation field will be presented. Only the basic principles will be discussed together with an opinion, strictly that of the authors, as to the future of each device as a potential solution to the reentry blackout problem. A number of references will be found to the aerospike antenna. A flight test of this particular device was also included in the present program and is reported in Ref. 10. The frequent references stem from this fact and are not intended to indicate special promise of this technique over others. Indeed, as the following pages will show there are very definite limits to the conditions under which the gas spike may be operated successfully.

II. ELECTRON BEAM

An electron beam, current-density modulated at microwave frequencies, has been proposed. A longitudinal mode is induced in the plasma by the modulated electron beam. At a plasma-vacuum interface, a transverse mode is excited (in order to satisfy the boundary conditions). It is said there is strong coupling between the longitudinal plasma and the transverse radiation modes.

A situation which reasonably approximates the plasma-vacuum interface is the shock front of a reentry vehicle. An inhomogeneous plasma layer lies between the vehicle surface and the shock front. A crude way of looking at the radiation mechanism is that of a transmitting monopole (no receiving mode) on a lossy ground plane (plasma-vacuum interface).

Certain laboratory tests are appropriate in order to establish the utility of this technique. The electron beam fluorescence technique used in the study of gas flow provides an extensive background technology. An excellent review of this technique has been published recently[7]. The basic question is: for a given accelerating potential, what is the behaviour of the beam as the ambient gas density (plasma) is increased? Such questions as beam penetration, spreading or scattering and transverse energy distribution as a function of gas density remain to be answered (see Ref. 7, p. 12).

If the answer to this fundamental question is favorable then verification of the radiating mechanism over the same dynamic range of reentry density conditions is incumbent. This could be performed by a test model in a shock tube. Although actual in-flight conditions are impossible to obtain, the upstream flow would be sufficiently underdense so that an interface could be effected.

Certain other fundamental questions arise, such as the effect of flow on the beam. It appears that there may be little gas focusing as compared to a stationary gas. When considering a complex reentry flow, separation, variation of angle of attack, etc., the problem is compounded. There are attendant questions in gun design, beam injection and pumping. Presumably these have been well studied (Ref. 7, p. 56).

III. ENHANCED ELECTRON ATTACHMENT BY RF HEATING

One method that employs a new electrophilic process has been reported[8]. O_2 was injected into the exhaust of an N_2 arc jet with exit conditions $\rho/\rho_0 \stackrel{<}{\sim} 3 \times 10^{-4}$ and a temperature of approximately 3000°K. The electron density was measured along the jet axis. Next an RF heating coil was placed such that the jet was coincident with the coil axis. A quick engineering calculation estimates the heated electrons to be of the order of 10 eV (vs. 0.3 eV thermal). A significant reduction in electron density was then observed as a function of O_2 mass addition, with the highest O_2 - N_2 ratio approximating that of air. No indication was given as to the effect of varying the RF heating power in the experiment.

Referring to the experimental attachment cross section[9] for O_2, it is seen that the first resonance is 1.3×10^{-18} cm^2 at an electron temperature of 6.2 eV. Our estimate of a temperature of approximately 10 eV for the RF heated electrons is admittedly crude, due to insufficient information. However, it does appear that the reduction in electron density reported[8] was indeed an attachment resonance effect. Specifically,

the low temperature 0.3 eV electrons were heated in order to utilize the maximum attachment cross section of O_2.

This is an interesting approach. At the nozzle exit conditions reported, there is certainly sufficient O_2 to act as a getter. Unfortunately, for most reentry trajectories O_2 is almost entirely dissociated. The attachment cross section for O is quite different and the heating of the free electrons would seriously impede the attachment process. The use of other electrophilics was suggested, in particular SF_6. The first attachment cross section maximum of SF_6 is at zero eV[8] and decreases monotonically at least to 1.2 eV. For this getter a "cooling" of the free electrons is dictated.

Injection of water, which has a first attachment cross section maximum at 6.4 eV[8], might prove to be useful. Certainly for any reentry situation one would have to rely on non-equilibrium conditions, prior to complete dissociation. This could be accomplished by injection just upstream of the RF heater. Certain halogen compounds could also be used but they would require much less free electron heating. The appeal of the original scheme is lost if injection must be employed since in that case the getter O_2 was already present.

IV. SHAPING

A. Spikes and Fins

Local aerodynamic shaping was listed by the aerospace group as having the most promise as an alleviation technique. The idea is to extend a rod or a fin from the vehicle. The shock structure and flow pattern about this appendage, from an RF standpoint, would have vastly improved characteristics when contrasted with those about the main body. This was confirmed by the recent flight of Trailblazer II - OSU 4.[10] The main problems with this technique are vehicle stability and heat transfer rates to the appendage. (These problems were not encountered with Trailblazer II - OSU 4.) If the vehicular stability problem can be resolved by one means or another, then certainly metal spikes have their place in the bag of alleviation tricks. The spike can be expendable, as for example a monopole that is projected into the flow by mechanical means at a rate such that a constant length is maintained. This would provide an inexpensive and fairly reliable system. The same technique could be applied to an expendable fin system.

B. Aerodynamic Gas Spike

The Aerodynamic Gas Spike is a device that seeks to combine the benefits of aerodynamic shaping and coolant injection, while avoiding the disadvantages attendant on any permanent fin or pointed nose structure. Its prime function is the simulation of a pointed nose by the ejection of a narrow supersonic jet of helium. Any cooling effect is secondary and is likely to be of benefit mainly in protecting the vehicle surface by providing a cooler boundary layer. Mixing with the shock layer is not likely to be sufficient to have significant effect on the plasma. The benefit here will be obtained mainly by reduction of the shock angle. Formation of the gas spike requires that it be directed along the stagnation streamline. Any significant transverse flow will result in collapse of the spike. This would mean that in a lifting vehicle operating at a variable angle of attack it might be necessary to employ a number of alternate nozzles so that the jet would always be at or near the stagnation point.

To properly simulate the conditions of lifting reentry an experiment must be performed with a blunted payload, where the thickness and angle of the shock layer are such as would normally produce blackout at the radio frequency or frequencies used for the test. A successful test of the gas spike must demonstrate that communications can be restored under these conditions by means of this device.

A proper relationship between the nose radius and spike length is essential to a successful experiment. This relationship is illustrated in Fig. 1. The figure shows a nine degree half-angle cone with a base diameter of nineteen inches, the usual payload configuration for the Trailblazer II vehicle. However, three different nose arrangements are shown. In each case the nose is spherically blunted with radii of: 0.75, 3.0, and 6.0 inches respectively. The jet length assumed is approximately five inches. This is also shown in the figures together with the approximate shock shape for each of the three cases both with and without the gas spike. In each case there are two flow regions of prime importance. The first of these is the stagnation region, that region around the nose of the vehicle where the air has passed through a near normal shock front and is at a greatly elevated temperature and density. The width of this region is in the order of one nose radius and its thickness about one twentieth of a nose radius for the flight conditions of a Trailblazer. The second region is that behind the oblique shock to the side of the vehicle. The shock angle depends on the Mach number and on the cone angle and is thus essentially the same for each of the three cases illustrated. At the higher altitudes there is a third layer of major importance; the boundary layer. This is the layer close to the vehicle surface formed by the gases escaping from the stagnation region. Its thickness is also dependent on nose radius.

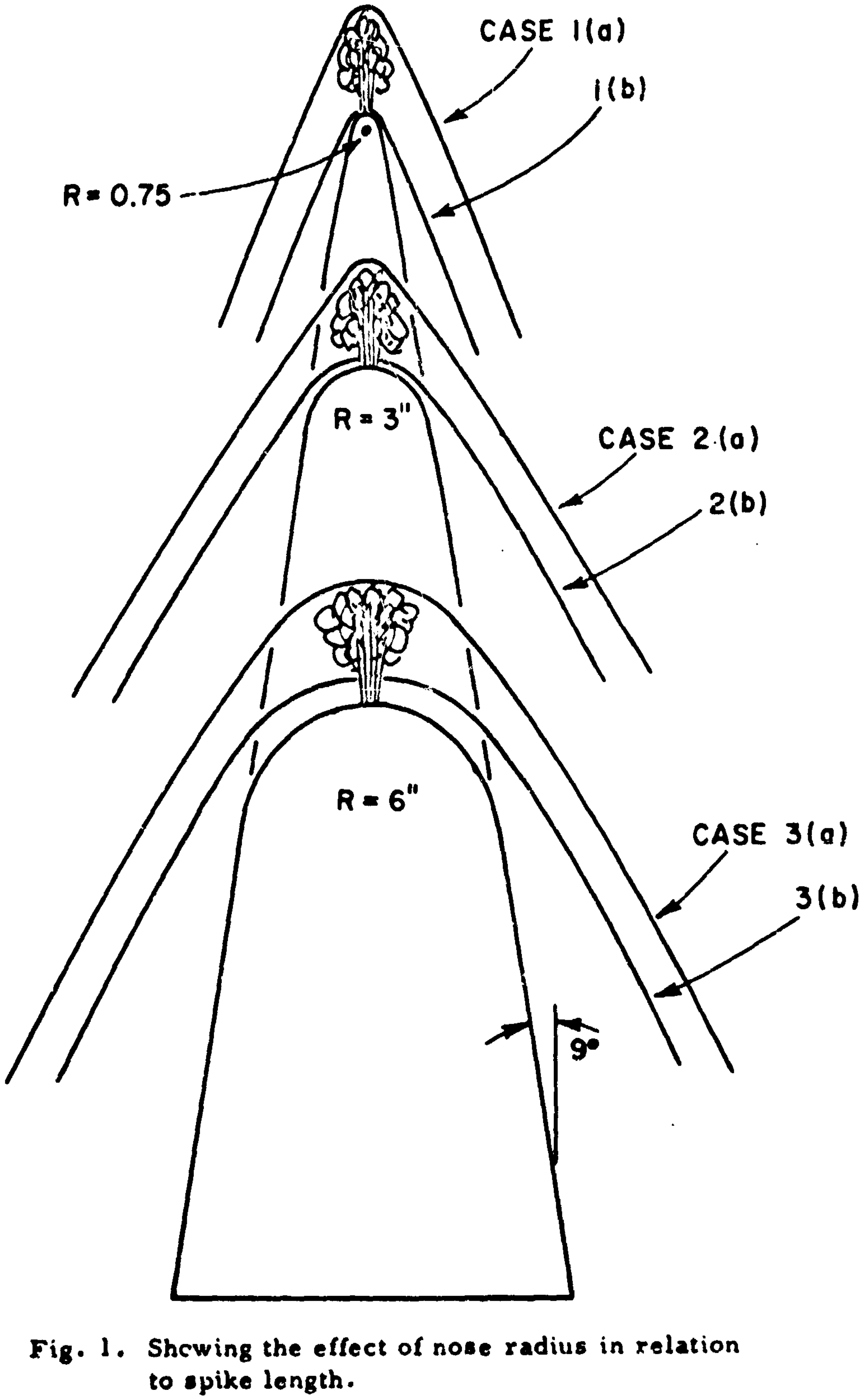


Fig. 1. Shcwing the effect of nose radius in relation to spike length.

In the first case illustrated (nose radius of 0.75") the boundary and shock layers are relatively thin. Conditions are thus approaching those of a pointed vehicle and hence do not represent severe communications problems. Activation of the gas spike produces only a relatively small change in the conditions. The effective nose radius of the jet is of the same order as the vehicle. Thus the jet moves the bow shock forward but does not substantially alter its shape.

Case 3 shows a nose with a six inch radius. This represents the other extreme in relation to spike length. The spike length is insufficient to force the shock front clear of the vehicle shoulders, thus the center portion of the shock front is still dominated by the nose radius rather than the spike. The plasma density is therefore high throughout the central region and r.f. conditions are not significantly improved by the spike. Thus in both cases 1 and 3 the spike has little effect: in case 1 because the effective diameter of the spike is similar to that of the vehicle, and in case 3 because the spike is too short to override the dominant effect of the large nose radius.

Case 2 represents the optimum condition for spike operation. This is still the case of a blunt vehicle with a strong normal shock and dense stagnation region 2(b). However, the spike length is now such that it can hold the shock front clear of the vehicle shoulders with the result that the flow is now dominated by the spike rather than by the nose radius. There is thus a considerable reduction in the volume of high density plasma. There will still be a blob of plasma, where the flow stagnates at the tip of the jet, which will be opaque to an antenna mounted coincident with the nozzle. However, the oblique shock along the sides of the spike will be transparent. There will thus be only a nominal degree of aperture blocking. The optimum nose radius vs spike length for a fixed gas supply system must be determined by appropriate wind tunnel tests.

The most suitable antenna from an installation and data analysis standpoint appears to be a dielectric-loaded open-ended waveguide. The dielectric loading will enable the edges of the antenna to be kept within the clear area and the nozzle can be formed within the dielectric, thus permitting the jet to be located at the exact center of the antenna. Some improvement may be expected in the pattern shape because the antenna is mounted on a curved surface rather than a flat ground plane. Transmission of course is effected through the oblique shock and not in a forward direction.

C. Aerospike Antenna

This concept is basically a combination of an extended rod and gas spike. Most of the comments and limitations that applv to both would apply to the aerospike. Certainly a very small or zero angle of attack is a necessity to maintain the gas spike portion of the aerospike. The intended purpose of the Trailblazer II - OSU 4 flight[10] was the verification of this concept. Due to late opening of the valve the gas spike was not established. However effectiveness of the extended metal rod antenna was clearly demonstrated as VHF communications were retained throughout the reentry period. The additional weight and system complexity introduced by the gas spike feature does not appear to be warranted, or in fact needed, if an adequate rod antenna is used.

D. Large UHF and Meterwave Antennas

The flight of Trailblazer II - OSU 4 demonstrated that a VHF signal would penetrate a thin plasma sheath which was well beyond cut-off. The effect was primarily attributable to signal penetration up to the plasma skin depth. Throughout the reentry period the antenna was well matched, the power reflection coefficient never exceeding 25% and typically 10%. There was some plasma-antenna current interaction indicated by a change in effective length. Some evidence of "plasma tuning" was indicated by reactive excursions from the driving point impedance characteristic. "Plasma tuning" has been considered by different researchers including this laboratory[11]. Due to the wide dynamic range of plasma conditions experienced during a typical reentry, it does not appear to be a particularly helpful approach. If the antenna is matched to its environment during reentry, then the two possibilities are transmission through and absorption by the plasma sheath. An initial mismatch to allow for plasma tuning is avoiding the issue.

If there is no specific frequency requirement (e.g., ECM) then application of the lower frequencies should be considered. One might consider a design such that $\lambda \stackrel{\sim}{>} 2L$, where L is the vehicle length. For longer vehicles one might not be able to meet this condition. Excitation of the after body in the expanded flow region is then a possibility. In any case the concept is to utilize the plasma skin depth penetration. The radiation pattern should be "dipole-like", at least if there are no wings or other major protrusions. Before an antenna design for a given reentry vehicle is established, it would be necessary to investigate the flow fields and their effect on the radiation for the important aspect directions. Determination of the dominant attenuation mechanism (shock layer, boundary layer, wake, etc.) should be predetermined, probably by wind tunnel experiments.

There are other considerations, such as ground support, for a non-standard frequency. There is probably adequate system margin down to 10 MHz[5].

V. THE MAGNETIC WINDOW

The idea of a magnetic window, that is an r.f. window through the plasma sheath created by a strong d.c. magnetic field, has been around almost as long as the reentry blackout problem itself. It has always had a strong appeal to communications engineers, probably because it is an electromagnetic solution to an electromagnetic problem. It also creates less conflict with vehicle aerodynamics than most other alleviation techniques. The use of shaping or the injection of any material raises many questions with regard to the overall integrity of the vehicle as well as the aerodynamic problems associated with the technique itself. While a very strong magnetic field (magnetic forces comparable with inertial forces) can influence the flow of an ionized gas[12] this is not generally the case for the field strengths required to create a magnetic window and the relatively low percentages of ionization existing in reentry plasmas.

The difficulty with the magnetic window has always been the strength of the field required. If the plasma is only slightly overdense a moderate magnetic field might yield some improvements. For greatly overdense plasmas, however, and while the exact field required varies somewhat with the chosen mode of transmission, it is generally necessary that the field be sufficient to produce a cyclotron frequency equal to or greater than the frequency which it is desired to transmit or receive through the plasma sheath.

Figure 2 shows the magnetic field required to produce various cyclotron frequencies. The relationship is linear. Thus quite a modest field can create a window at a frequency of a few hundred megacycles while the field to permit transmission at 100 GHz might well be prohibitive in a flight situation. Nevertheless the field to maintain transmission to X-band (5000 gauss) not at first sight appear extreme. However, a major difficulty lies in the fact that this field must be maintained throughout the plasma layer. Since the magnetic field due to a solenoid is subject to a cubic law decay the field at the poles of the magnet must frequently be many times that at the outer edge of the sheath. It is evident from this that a magnetic window may well work better where the sheath is physically thin but of high density, as for example near the stagnation point.

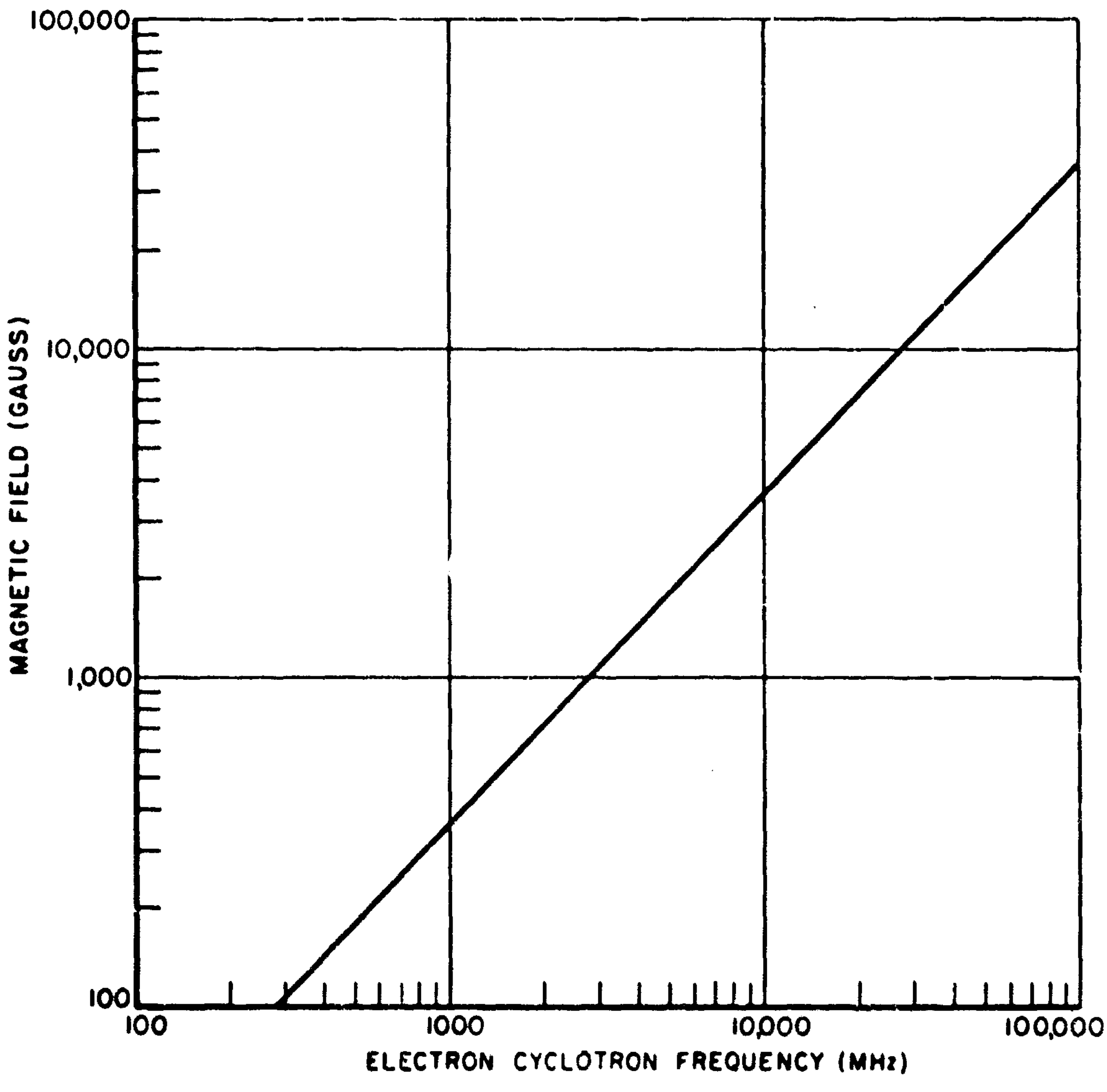


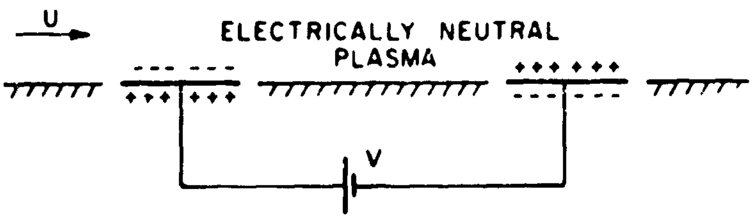
Fig. 2. Magnetic field versus cyclotron frequency.

It is this need for very high fields at the magnet poles which has so far kept the magnetic window off the list of practical alleviation devices. The fields required are greater than it is possible to obtain with permanent magnets and the power and cooling requirements for electromagnets make them impractical. This was the situation at the time of the Aerospace Corporation review in 1966. In the last few years, however, superconducting magnet technology has made considerable progress. Such magnets have ceased to be a laboratory curiosity and now offer a practical way of obtaining much stronger fields in less space than was previously possible[13]. In addition to offering advantages in research applications, machines employing superconducting magnets have been shown to be more economical than their more conventional counterparts[14]. This passing of the economic barrier is certain to spur further developments. Thus the time appears ripe to take a further look at the superconducting magnet as a reentry blackout control device.

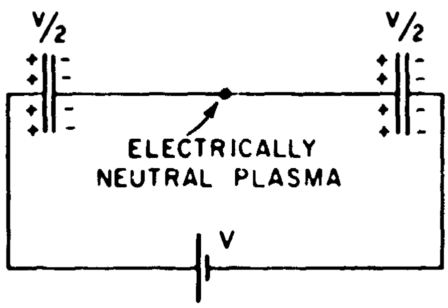
VI. ELECTROSTATIC CHARGE COLLECTION

Experiments have been performed on a method of collecting free electrostatic charges from a plasma. An electrostatic field is applied to the flowing plasma by plates in the channel wall. This field deflects free electrons which are then over the plates, thus reducing the electron density in the downstream region. Decreases in electron density of better than an order of magnitude have been achieved for initial electron densities of 10^{10} to 10^{11} el./cc. This technique does not seem to be as effective for larger electron densities, however a series of such collecting plates alternately polarized may overcome this difficulty. In application, a series of electron collecting plates could be placed on the vehicle surface so that shock layer gases would pass over the plates, losing electrons before reaching the antenna. If the electron density in the vehicle boundary layer is much higher than that in the inviscid shock layer, this method may be a feasible way of reducing the peak electron density above the antenna. The proposed method with equivalent circuits is shown in Fig. 3.

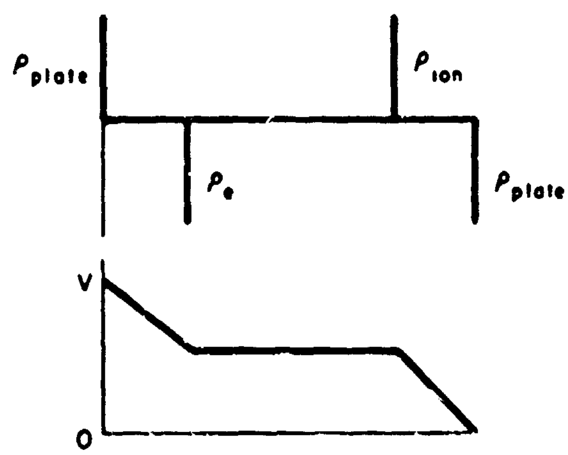
The limiting feature of the method is the "absorption" rate of electrons and ions (charge neutralization) at the electrodes. A detailed study of electrode materials and electrolytes which would react favorably with the ionized air species is required. Gas tube technology, e.g., thyratrons could prove useful in further investigations.



(a) FLOW OVER ELECTRODES



(b) EQUIVALENT CIRCUIT OF 1a



(c) CHARGE AND VOLTAGE DISTRIBUTIONS OF 1b

Fig. 3.

VII. CONCLUSIONS, THE OUTLOOK FOR REENTRY BLACKOUT ALLEVIATION

It is fairly evident that there will be no universal solution to the blackout problem. For example the requirements of a radioaltimeter on a pointed ballistic vehicle may be expected to be quite different from those of a voice channel on a manned, lifting vehicle reentering at a high angle of attack. Thus so far as the overall solution of the problem is concerned it is highly desirable that research and development continue on those techniques which offer most promise of a practical solution.

The selection of a particular system and the finalization of the design parameters can only be made with a specific application in mind. Thus it will take a specific mission requirement to force the final development stages of virtually any alleviation technique. The available alleviation methods range from the very simple to the very complex. The communications design engineer faced with a specific problem must therefore make his choice on the basis of the simplest method which will achieve the desired result. In making the initial selection questions are likely to be asked in about the following order:

(1) Can proper choice of antenna location solve the problem?

(2) Does the signal loss result from detuning of the antenna alone or is there substantial absorption by the plasma? If the former can a broadband or tunable antenna solve the problem?

(3) Is the problem caused by contaminants in ablation by-products? Is it possible to replace the ablator with a cleaner material or at least replace that portion of it immediately upstream from the antenna?

(4) Is the problem solely due to antenna breakdown precipitated by the shock induced pre-ionization? If so can the problem be solved by a reduction in power level, by relocating the antenna or by increasing the area of the antenna aperture thereby reducing the local field intensity?

(5) Can the frequency be shifted up or down to help the situation? The low limit is determined by channel availability, bandwidth limitations and antenna size. The upper limit is set by atmospheric absorption which becomes significant above 40 GHz. Any frequency

change is of course dependent on availability of ground facilities and other system constraints.

(6) Can some advantage be taken of vehicle shaping? This could simply be another way of asking question (1). Alternatively the possibility of modifying the nose or some fin structure to achieve a more pointed shape and hence reduce the plasma density might be considered. The use of an expendable hard spike might also be considered at this stage. It should be mentioned, however, that any changes in shape are apt to prove controversial. What often seems like a minor change to the communications engineer, often fills the vehicle designer with horror! This should serve to stress the importance of designing the system as a whole. It is essential that engineers and scientists from different disciplines understand and cooperate in solving each others problems.

(7) Lastly is a direct attack on the problem required to solve the problem? The use of a magnetic window, the injection of a coolant or electrophilic or any of the more complex techniques requiring special equipment and/or expendable materials would fall in this category.

In the event that one of the more complex systems is required there are many factors to be considered in the selection and in all cases further development is required to produce an operational system. So far only limited flight tests have been flown, for any of these advanced techniques. The most extensive tests have been those on water injection by NASA as part of the RAM and Gemini programs. OSU ElectroScience laboratory has flown a gas spike experiment; the results were inconclusive. Aerospace Corporation has been active in the injection of electrophilics. This is the extent of flight testing of alleviation techniques to date. All these tests have been of the fluid injection type although each has had a different objective. They all suffer from the common drawback that very substantial quantities of expendable material are required if a window is to be kept open for any length of time. There are also other limitations characteristic of the individual systems. Coolant injection can probably be beneficial in any situation where sufficient material can be injected into the troublesome portions of the sheath. Since the process is one of simple heat exchange the coolant required is considerable. If it is the shock layer that is troublesome, rather than the boundary layer, there is also the problem of obtaining adequate penetration and mixing. Electrophilics only work when the temperature is around 3000°K or less. Above this the attachment rate is likely to be too

slow and above 3000°K the injected material itself will ionize and probably aggravate rather than help the situation. Thus electrophilics are only likely to work in a non-equilibrium flow where cooling has already occurred by expansion or coolant injection. In the latter case a combination coolant-electrophilic injectant could be beneficial. In equilibrium flows at 2000°K there is not likely to be any blackout problem to begin with. The gas spike is a form of vehicle shaping. However, it requires rather restricted conditions. The gas must be ejected along the reverse stagnation streamline, and flow conditions must be such that the spike length is comparable with the characteristic body dimension at the point of injection. These are severe restrictions on a vehicle of large dimensions or one which is required to maneuver. Both these characteristics are found in manned lifting vehicles.

So far no flight tests have been performed with any non-injection device of the more sophisticated category. This is felt to be the most serious deficiency in the field at the present time. The Air Force Avionics Laboratory is currently planning flight tests of both an electron beam and a superconducting magnet. The electron beam undoubtedly has shortcomings. It is strictly a transmitting device; reception is not practicable. Also the ability of the beam to penetrate the sheath at any but the higher altitudes is open to considerable question. The superconducting magnet on the other hand shows considerable promise at this time in the light of recent developments in cryogenics and the time is definitely right for flight testing this device. Like the injection techniques, the magnet uses an expendable material, liquid helium, for cooling. However, unlike the injection devices unless cryogenic refrigerators are used the amount of coolant depends on the total length of the mission and not on the duration of the blackout. Thus it appears ideally suited to earth orbital missions such as the Air Force might fly where the total mission time is in the order of a day but the reentry may last 30 minutes. For lunar or planetary missions having comparatively shorter reentries but with mission time measured in weeks, injection techniques may well have the edge if space qualified helium liquifiers are not available.

In conclusion therefore it may be said that flight testing of injection devices for blackout alleviation is still in the early stages and should continue. It is also of utmost importance that flight tests on non-injection devices be conducted at the earliest opportunity. Of the possibilities in this category the superconducting magnet shows considerable promise at this time and should receive high priority.

REFERENCES

1. Electromagnetic Effects of Reentry, Selected papers from Symposium on Plasma Sheath Its Effects on Communication and Detection, 7-9 December 1959. W. Rotman and G. Meltz, Ed., Pergamon Press, (1961).

2. Electromagnetic Aspects of Hypersonic Flight, Second Symposium on the Plasma Sheath, Its Effect Upon Reentry Communication and Detection, 10-12 April 1962. W. Rotman, H.K. Moore and R. Papa, Ed., Spartan Books, Inc., Baltimore, (1964).

3. Proceedings of the Third Symposium on the Plasma Sheath-Plasma Electromagnetics of Hypersonic Flight, 21-23 September 1965.
   I. Radiation characteristics of plasma-covered antennas.
   II. Electrical properties of shock-ionized flow fields.
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   W.Rotman, H. Moore, R. Papa and J. Lennon, Ed., AFCRL-67-0280 (Vols. I, II and III), May 1967, Spec Repts. No. 64 (I, II, III) Office Aerospace Research, USAF, Bedford, Massachusetts.

4. Proceedings of the Conference on the Applications of Plasma Studies to Reentry Vehicle Communications, I., 3-4 October 1967, Sponsored by USAF Avionics Laboratory, Wright-Patterson Air Force Base, in conjunction with The Ohio State University Electro-Science Laboratory. (AD 830 456).

5. Lifting Reentry Communications, Plasma Research Laboratory, Aerospace Corporation, El Segundo, Calif., Aerospace Rept. No. TR-669(6220-10)-3, Vol. I and II. May and September 1966
   I. A comparative evaluation of potential systems.
   II. Systems calculation.

   AF Rept. No. SSD-TR-66-73, Vols. I and II.

6. "Trip Report Minutes on the Discussion of Communication Through the Reentry Plasma Sheath, Part I."(U), Report 2438-1, 1 June 1967, (Report Secret). Part II, Report 2438-2, 1 October 1967, ElectroScience Laboratory, The Ohio State University Research Foundation, prepared under Contract F33615-67-C-1643, for Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. (AD821 931)

7. Muntz, E.P., "The Electron Beam Fluorescence Technique," NATO-AGARDograph 132, (December 1968). (AD 692 860).

8. Jacavanco, D.J., "Electron Reduction in the Reentry Plasma Sheath," AFCRL-69-0154, Phys. Sci. Res. Pap. No. 375, OAR, USAF, (April 1969).

9. Buchel'nikova, I.S., "Cross Sections for the Capture of Slow Electrons by O_2 and H_2O Molecules and Molecules of Halogen Compounds," JETP, 35 (8), 783, (1954).

10. DeVore, R.V., R. Caldecott and P. Bohley, "VHF Reentry Communications; Flight Test Measurements Using a Trailblazer II Vehicle and Including a Test of the Aerodynamic Gas Spike," Report 2438-5. (Report in preparation).

11. Christen, R.E., "Investigation of the Interaction Between a Longitudinal Slot and a Plasma," Report 2146-4, 15 June 1966, ElectroScience Laboratory, The Ohio State University Research Foundation; prepared under Contract AF 33(615)-3466 for Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. (AD 487 995)

12. Hooks, L.E., "Simplified Magnetoaerodynamic Flow Relations for Axisymmetric Blunt Bodies," Report 2146-5, 29 July 1966, ElectroScience Laboratory, The Ohio State University Research Foundation; prepared under Contract AF 33(615)-3466 for Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. (AD 800 431)

13. Laverick, C., "High Field Superconductor Technology," IEEE Spectrum, p. 63, (April 1968).

14. Appleton, A.D., "The Superconducting Motor," Industrial Research, p. 72, (September 1969).

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13. ABSTRACT

A review of the state of the art in techniques for alleviating radio blackout during atmospheric reentry is presented. The various techniques currently being studied by those organizations interested in this problem include: injection of coolants and electrophilics, magnetic windows, electron beam devices, vehicle shaping, electrostatic charge collection and the use of high and low frequencies. The relative advantages and disadvantages of these methods are discussed. With the exception of simple, pointed, ballistic vehicles the only flight experiments to date, concerned specifically with alleviation, have been on injection devices. The report concludes that these devices have many limitations and that the time is come to flight test other types of system, the magnetic window being the most promising in the light of recent developments in superconducting technology.

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